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REPORT

Satellite sound broadcasting to fixed, portable and mobile radio receivers

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THE BRITISH BROADCASTING CORPORATION

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Summary

Direct broadcasting by satellite (DBS) of television signals to the home has received much attention recently; in contrast, less attention has been paid to sound-only (i.e. radio) broadcasting from satellites. This Report reviews the present range of terrestrial sound broadcasting and explores the possible scope and technical feasibility of using satellites. Satellite broadcasting of sound programmes to receivers of all types, including portable and mobile, situated in national or regional areas appears technically practicable, but there are problems to be overcome. The most significant are regulatory in nature, in particular there is no appropriate frequency allocation. A new system possibility is presented using digital modulation which has a number of advantages, including potential for good spectrum utilisation. Various technical details require further study to produce a system of optimum performance, flexibility and spectrum efficiency.

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SATELLITE SOUND BROADCASTING TO FIXED, PORTABLE AND MOBILE RADIO RECEIVERS

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1. Introduction

Direct Broadcasting by Satellite (DBS) of television signals to the home is now a well established concept. Its technical feasibility has been demonstrated beyond doubt, and a regulatory framework has been established[1,2] whereby specific frequencies (in the vicinity of 12 GHz) and orbital positions have been allocated for almost every country in the world. A satellite serving Japan is already in operation and other countries plan to start DBS services in the near future.

But what about sound radio, the medium by which broadcasting first became established and which still has a major following? Is the use of a satellite to broadcast sound radio programmes feasible and does it offer any advantages?

Sound broadcasting is possible in the 12 GHz band used for television DBS, although the range of applications is limited. There are two general approaches. In the first, additional sound channels are transmitted along with a television signal, by using the EBU MAC/packet standard,[3] or by using additional subcarriers with analogue or digital modulation. The second approach to the use of the 12 GHz band simply dispenses with the television signal altogether and uses the whole channel for sound (and, perhaps, data) signals; an example is the proposal[4] to use one of the DBS channels allocated to the Federal Republic of Germany.

Although sound programmes unrelated to any television signal can and will be broadcast at 12 GHz by these means, they do not answer all the expectations of a radio service. They require an antenna of significant directivity and physical size, which must therefore form part of a fixed installation – comparable in scope with that recommended for high-fidelity stereo reception of present VHF/FM sound broadcasts but requiring more critical antenna alignment. However, users of fixed installations form only part of the audience for present radio broadcasts. A radio receiver can be used almost anywhere, including situations where it would be inappropriate to look at a picture display; indeed, the use of portable receivers and receivers in vehicles is very widespread. The source of programmes may be local, regional,* national or from some distant country. It is in this broader context that this Report will examine the possibilities for satellite sound broadcasting.

Satellite broadcasting of sound radio may be attractive for a variety of reasons. Of special value to developing countries is the availability of nation-wide coverage without the need to establish a network of terrestrial transmitters and the supporting infrastructure. To developed countries it offers an opportunity (perhaps the last) to remedy some of the drawbacks and deficiencies of existing methods of sound broadcasting.

2. Sound broadcasting at present

A convenient way to describe the present diversity of terrestrial sound broadcasting is to consider the use made of each band of frequencies.

(a) LF and MF

These bands are used mostly for domestic broadcasting, ranging from low-power local services to high-power networked national services. Some international broadcasting takes place and there is also limited scope for listening to the domestic services of other countries. This is assisted by the greater range which may be achieved, especially at night time, by means of ionospheric propagation. However, this also means that the area which is served with good quality from any transmitter actually contracts at night because of the increased interference from distant stations using the same or adjacent channels.

The channel spacing is generally 9 or 10 kHz (depending on the part of the world) and conventional double-sideband amplitude modulation (DSB AM) is generally used.† The audio bandwidth is thus restricted. A ferrite rod is the usual antenna for portables and also for most fixed receivers, while a short whip or telescopic rod is currently most common for vehicles.

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* 'regional' is used here in the non-ITU sense to mean 'part of a country'.

† Various forms of AM stereo are in service in the USA and elsewhere.

(b) HF

The HF bands are heavily used for international broadcasting but they are also useful for national broadcasting where countries are large and/or in tropical regions where LF/MF is less suitable. For this reason, certain lower-frequency HF bands are reserved for national use in tropical regions. Propagation via the ionosphere is essential to HF broadcasting and is subject to variation on a daily and seasonal basis as well as a longer term variation (of approximately 11 year period) associated with solar activity.

The channel spacing is generally 5 kHz. DSB AM is used although there has been much discussion aimed at a gradual transfer to single-sideband operation to improve spectrum efficiency. Portable receivers typically use a simple telescopic rod while fixed receivers may be equipped with a more elaborate antenna.

(c) VHF

This band is used for domestic broadcasting, ranging from local services to national transmitter networks. Propagation is essentially line-of-sight, somewhat extended by diffraction and refraction. Propagation over longer distances than normal may occur infrequently by various mechanisms; some account is taken in planning of the interference this may cause.

Wideband frequency modulation (FM) is used; various subcarriers may be added to the baseband audio signal in order to transmit stereophonic signals, supplementary monophonic signals or data. The channel spacing recommended by the CCIR is 100 kHz, but the occupied bandwidth is greater than this so that adjacent channels cannot be used to serve the same area. Usual antennas are a telescopic rod for portables and a telescopic rod or whip for vehicles. Fixed installations seeking the best quality reception of stereophonic signals may use multi-element antennas. Reception can be degraded by multipath effects, especially in vehicles.

(d) General comments

All the bands used for sound broadcasting are congested. They are used to provide services on a scale ranging from local to worldwide, for reception with portable receivers, in vehicles or in the home. The proportion of listening performed using receivers equipped with elaborate antenna installations is small.

The quality of reception afforded by the various bands may generally be ranked in the order of VHF (best), then LF/MF (quality limited by bandwidth and interference), and finally HF (worst, quality limited by bandwidth, variable propagation, and interference including jamming). While VHF broadcasting has for many years set the standard for domestic high-quality sound reproduction, it now faces challenges from other programme sources, especially those using digital techniques. Compact Disc is now widely available, while the first broadcast service of digital sound directly to the home is likely to be for television, either via DBS or the proposed addition of digital stereo sound to the UK terrestrial transmissions.

Historically, the developed countries have established first LF/MF and then VHF transmitter networks for their domestic services. Once the VHF band is fully used there is no further scope for expansion. For a developing country, especially if it is large, HF may be the only economic terrestrial solution since complete coverage could require a network of several transmitters at MF and still more at VHF.

3. Where could satellite sound broadcasting fit in?

The title of this section is really several questions in one. We have seen in the previous section the wide range of roles that can be played by conventional radio broadcasting – which of these could be performed by broadcasting from satellites? Would there be any advantage? There is also the question of how satellite broadcasting of sound radio could fit into the present regulatory structure – in particular, a recurring question is: what frequencies can be used?

3.1. Frequency allocation

The internationally agreed allocation of frequencies to services is given in the Table of Article 8 of the Radio Regulations of the International Telecommunications Union (ITU),[5] and quite simply, there is no express allocation to sound broadcasting from satellites. Broadcasting from satellites is expressly permitted within various bands at 12 GHz and above. The 12 GHz band has already been planned for television although as already noted there is no reason why a television channel should not be used for other broadcasting purposes, such as multichannel sound radio, within technical constraints protecting other planned television services. However, use of frequencies as high as 12 GHz or greater is not compatible with the concept of portable or mobile reception of sound radio because of the receiving antenna requirements and propagation characteristics.

The 2.5 GHz band may be used for satellite broadcasting, but, by Footnote 757 of the Radio Regulations, it is limited to 'national and regional systems for community reception', (i.e. using large antennas) and is subject to power-flux density (PFD) limits. These limits are intended to protect other services with which the band is shared. A system might be devised which could permit reception, with a simple antenna, of signals satisfying the PFD limits by using digital modulation to spread the signal energy over a wide bandwidth (compared with that in which the PFD is measured). A high performance would be demanded of the receivers, and the link margin (see Section 4) would be very small; this is possibly satisfactory where the satellite is nearly overhead, as for tropical countries with a suitably placed geostationary satellite. Thus, as it stands, this band would not offer adequate reliability in all parts of the world while requiring a receiver of greater cost than desirable for this mass-market application. If it were not necessary to share the band the story would be different. Similar difficulties tend to rule out sharing of other bands as well.

Broadcasting from satellites in the UHF band is not expressly permitted in the Frequency Table, but Footnote 693 permits FM *television* in the band 620–790 MHz subject to PFD limits and the agreement of affected countries.

Satellite broadcasting is not permitted by the Radio Regulations at any frequency below UHF.

Thus there is at present no niche in the regulatory framework for satellite sound broadcasting. Recognising this, the ITU World Administrative Radio Conference (WARC) of 1979 adopted Resolution 505.[5] This notes that there is interest in broadcasting sound signals from satellites to portable or mobile receivers, that the most appropriate frequency range is 0.5 GHz to 2 GHz within which there is no allocation, that further studies and experimental demonstration of a working system would be desirable and that sharing with other services in the same band would be difficult. It then urges administrations to carry out experiments (within small sub-bands of the spectrum, by mutual agreement) and continue studies so that a later conference can consider the matter again. This has been done at the recent ITU Planning Conference for the Geostationary Satellite Orbit (WARC-ORB-85, first session) (proceedings unpublished at the time of writing) and the subject remains open for further study.

Nevertheless, it is clear that identification of an exclusive frequency band for future satellite sound broadcasting is required to permit efficient spectrum utilisation (for all services) on an international and preferably worldwide basis. The technical requirements of such a system (discussed later in this report) favour a frequency band located in the region of 1 GHz and an appropriate choice of system parameters could ease both the amount of spectrum required and the problems of other services sharing the band on a secondary basis. It is thus necessary for a long-term plan to be initiated at the second session of the Geostationary Satellite Orbit Conference (due to be held in 1988) to modify the International Frequency Table and permit a modest, but exclusive primary band allocation for satellite sound broadcasting. Sufficient time will need to be given in the plan to redeploy existing services which would be affected.

3.2. Choice of orbit

The geostationary orbit is most commonly considered for communications and broadcasting satellites. It is a circular orbit, lying in the equatorial plane, of radius 42,164 km and 24-hour period, such that a satellite appears stationary to observers on the Earth, with the obvious advantage that fixed, directive antennas can be pointed at it. However, when used to serve high-latitude countries, the elevation angle is small and the polar regions cannot be served at all.

Another orbit of interest is the inclined, highly-elliptical orbit commonly known as the Molniya orbit, after the class of Russian satellites that uses it. It has a 12-hour period and has the property that for about 8 hours in the 12, the sub-satellite point is almost constant in longitude, with a slow variation in latitude. This quasi-stationary state appears at longitudes separated by 180° on alternate orbits because the period of rotation of the Earth is 24 hours compared with the 12-hour orbit period. Thus, viewed from a country between 50°N and 60°N, such as the UK, a satellite could be made to be nearly overhead for 8 hours in every 24; thus three such satellites would be necessary to give continuous service. The high elevation angle reduces the risk of shadowing and multipath; it also permits use of a higher-gain antenna on vehicles: a beamwidth of 30° corresponding to 15 dBi gain might be used though some additional allowance for vehicle tilt on hills might need to be made. The main penalty is the need for 3 operating satellites for continuous service.

A Molniya orbit was proposed for a UK Communications Engineering Research Satellite.[6]

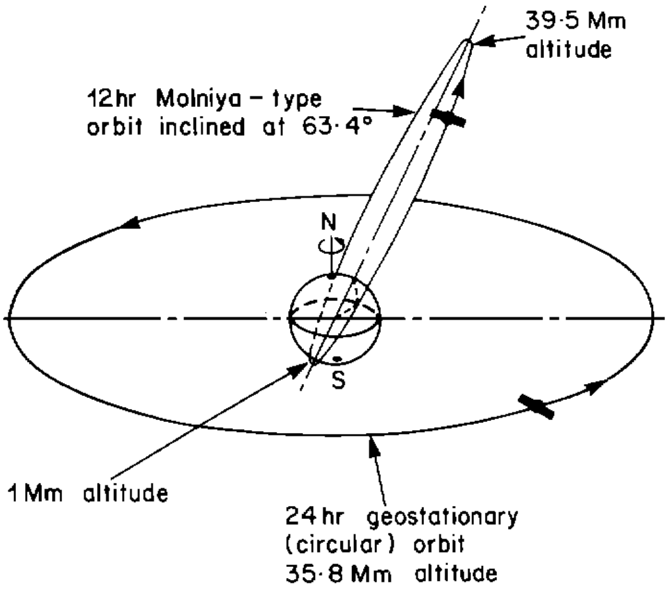
39·5 Mm altitude
12hr Molniya – type orbit inclined at 63·4°
N
S
1 Mm altitude
24 hr geostationary (circular) orbit 35·8 Mm altitude

Fig. 1 – Comparison of geostationary orbit with the proposed one of Molniya type.

One potential area of study was satellite communications with vehicles, a problem having much in common with sound broadcasting from satellites. Figs. 1 and 2 depicting the proposed Molniya orbit are adapted from Ref. 6.

It is unlikely that use of such orbits, differing from the geostationary one, will permit substantial frequency re-use by orbit separation, though some improvement in spectrum utilisation might be gained at the detailed planning stage if some countries opted to use different orbits, since more uniform power budgets would result.

3.3. Type of service – local/national/international

We have seen that conventional terrestrial radio is used on a scale extending from local (e.g. a small town) to international. What part of this range could be served from satellites?

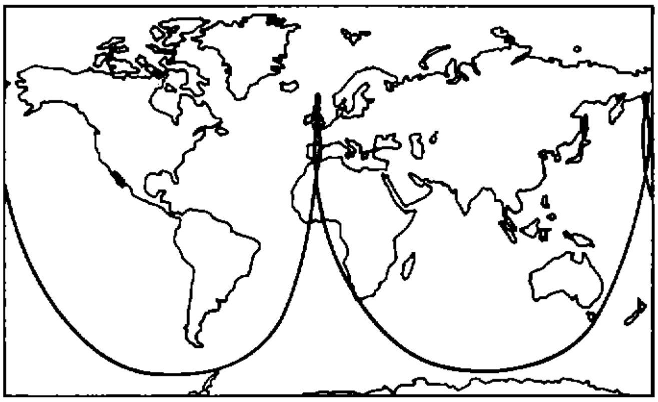

Fig. 2 – Locus of sub-satellite point for the Molniya-type orbit proposed for UK coverage.

To answer this question, let us first determine the angle subtended at a satellite by the various areas in question. Assume that the satellite is in geostationary orbit (radius 42,164 km). Other orbits may also be of interest; the Molniya orbit, at least, involves a similar distance. The mean radius of the earth is 6378 km so the angle subtended at a geostationary satellite by the visible part of the earth is clearly

$$2\sin^{-1}\left(\frac{6378}{42{,}164}\right) = 17.4°.$$

Beam sizes for national coverage can be taken from the values used in the 12 GHz DBS TV Plans.[1,2] In this case elliptical beams were assumed of a size which would include the country in question. In larger countries multiple beams were allocated. For example, the beam for the UK has dimensions 1.84° × 0.72° (to the −3 dB points). For very small countries such as Andorra a beam size of 0.6° was taken as being the smallest practicable although much larger than needed to serve the country.

The lower limit to beam size is set by two technical factors. One is the accuracy with which the satellite antenna can be pointed at the service area. The figure assumed in the WARC-77[1] Plan was a limit of 0.1° deviation in any direction. (In addition, a limit of ±2° was set on the rotation of an elliptical beam about its axis.) The second factor is the size of transmitting antenna required on the satellite. The half-power beamwidth ϕ_0 of a circular-aperture antenna of diameter D metres at a frequency f (GHz) is given[7] approximately by:

$$\phi_0 = \frac{21}{fD}\text{ degrees.}$$

(Strictly, the result depends on the detailed design.) The size of the satellite transmitting antenna is thus inversely proportional to beamwidth and frequency. Thus small beamwidths at low frequencies will be impracticable because the antenna will be too large to launch, see Fig. 3. It should be borne in mind that the antenna need not be a dish antenna – it could be a phased array – and that it is possible to design antennas which unfold in space once freed from the constraint of the launch vehicle. A further obvious question is whether a local service is not more easily provided by a single terrestrial transmitter.

The upper limit to beam size is set by the power available on the satellite – for a given desired PFD, doubling the coverage area doubles the required

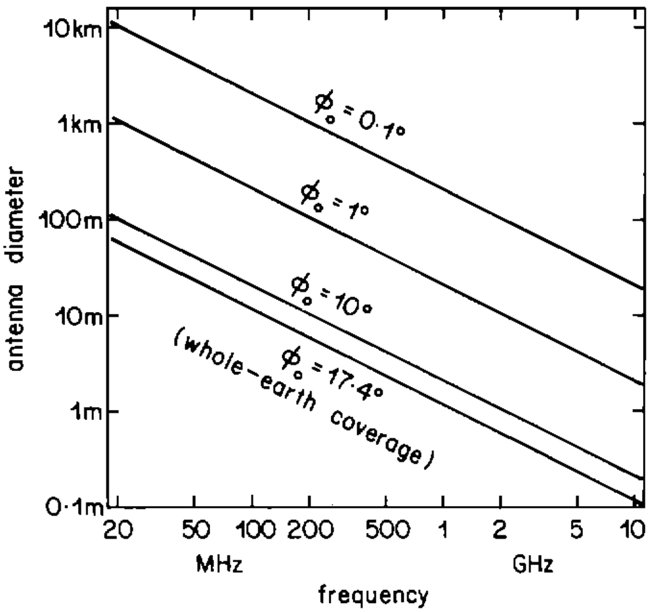

Fig. 3 – Size of transmitting antenna as function of frequency and half-power bandwidth ϕ_0.

transmitter power. The power required is also a function of other parameters of the system, some of which will vary with frequency.

To sum up, *local* services are unlikely to be provided by satellite because of the limitations of pointing accuracy and the size of the satellite antenna, and the fact that terrestrial transmitters can do this job perfectly well more cheaply.

At the other extreme, *international* broadcasting is possible technically, especially at the lower frequencies. Interest has been shown in the possible use of the 26 MHz HF band. This band is only of value for terrestrial broadcasting during the peaks of the sunspot cycle – when it is effective over long distances. During the rest of the cycle it remains dormant. Ref. 8 shows that the band could be used for international broadcasting from satellites. However, the proposal to do this did not gain sufficient support and the World Administrative Radio Conference of 1979 reduced the capacity of the band instead. In this context Article 30-2 of the Radio Regulations[5] should be noted, which states that in devising a satellite broadcasting service the radiation over other countries must be reduced to the maximum extent practicable unless an agreement is reached with these countries. The political climate for international satellite broadcasting is thus cool.

This leaves *national* and *regional* (in the sense of part of a country) services. These are technically feasible and offer certain advantages over terrestrial broadcasting. We shall now consider them in more technical detail.

4. Link budgets

So far we have considered what is feasible in terms of essentially mechanical constraints on the satellite – pointing accuracy, antenna size – but an equally important factor is the transmitter power required. This can be determined by constructing a power budget for the link, starting from the minimum received power necessary for satisfactory quality and accounting for all the losses encountered on the link to arrive at the transmitter power required.

Early work assumed the use of frequency modulation.[9] Sample link budgets for systems using frequency modulation having the same characteristics as used in terrestrial VHF broadcasting are presented in CCIR Report 955.[10] Use of FM in this way would permit the use of a simple frequency converter in front of a standard receiver.

On the other hand, it is interesting to consider the use of digital modulation since this can offer very high quality and a great degree of flexibility. For example the bit rate needed to carry a high-quality stereophonic signal can equally well carry two completely independent high-quality monophonic signals or a greater number of lesser-bandwidth signals. Thus a digital broadcast channel can carry, say, a stereo concert relay at one time and a multi-lingual news broadcast at another, the receiver reconfiguring itself automatically. The extra receiver complexity for digital modulation would at present incur a cost penalty, but significant progress is being made in mass-market digital integrated circuits. For example, at least one TV manufacturer is now producing receivers which use large-scale digital processing in place of analogue circuitry so as to reduce alignment costs. Digital audio processing is reaching the mass market via Compact Disc.

For reception in vehicles and by portable receivers, a simple antenna is desirable. For vehicles, which must follow the road round bends and over hills, significant directivity would in any case be undesirable since the orientation of the vehicle with respect to the satellite is arbitrary. The only exception to this is if the satellite is nearly overhead, as for low-latitude countries served by geostationary satellites or high-latitude countries served from a Molniya orbit. Ref. 10 assumes a receiving antenna gain of 3 dBi. For the same reasons of arbitrary orientation, and also because of Faraday rotation in the ionosphere, circular polarisation is preferred. However, cross-polar discrimination cannot be relied upon to assist frequency re-use, as was done in the TV DBS Plan,[1,2] for two reasons. In urban areas served at low elevation angles the signal will at times be received indirectly via reflection, whereupon the polarisation is uncertain. Secondly, the receiving antenna would have to provide significant cross-polar discrimination (perhaps 20 to 30 dB) over virtually half three-dimensional space. This would be difficult to achieve with the desired simplicity.

A fixed value of antenna gain implies that the effective area of the receiving antenna varies inversely as the square of frequency, so that the required PFD varies directly as the square of frequency. The link budget thus depends on frequency, even without considering any variation in the margin required for shadowing and multipath. We shall construct sample budgets assuming a frequency of 1 GHz.

Ref. 10 assumes a receive system noise temperature of 2000 K, but the detailed derivation is not given. It would appear to be dominated by the receiver front end, in which case even current technology offers a ready improvement. A receiver noise figure of 3 dB is now readily practicable. Ref. 11 suggests that a receive system noise temperature of 600 K is now practicable and we shall use this figure in our example. Note that at lower frequencies the level of man-made noise increases, especially in urban areas. This, together with the increased *physical* size of the receiving and transmitting antennas sets a lower limit to the usable frequency of a high-quality system.

The objective for received carrier-to-noise ratio (C/N) depends on the modulation system and also the quality objective. For the FM case, Ref. 10 takes the value of 10 dB – the FM threshold, corresponding to an audio signal/noise ratio of approximately 40 dB (weighted, mono reception). This does not represent very high quality, (about 'Fair' on the quality scale of CCIR Rec. 500), but it should be noted that a link margin of 6 to 33 dB is then built in to allow for the effects of shadowing and multipath,* so many locations will receive a stronger signal. A fixed installation using a carefully-sited, more elaborate antenna can then be assured excellent quality reception, possibly including stereo for which a much greater C/N is required.† Whether this variation of quality objective from mono mobile use to fixed stereo reception is acceptable may be open to question: stereo reception of terrestrial VHF signals in cars and by 'personal stereo' receivers is now very common. We may also note the high quality now achievable, both in the home and on the move, from digital equipment such as Compact Disc.

As an example of a digital system we shall assume that a bit rate of 728 kbit/s is transmitted using VSB 2-PSK modulation.[13] This bit rate is sufficient to carry two high-quality sound signals (a stereo pair or two independent signals) using near-instantaneous companding, and corresponds to a current proposal for adding digital stereo sound to terrestrial UHF television broadcasts. Preliminary subjective tests of the effect of transmission errors on this coding system suggest that a bit-error ratio (BER) of 10^{-4} corresponds to CCIR quality grade 4.5 (between 'Excellent' and 'Good') while a BER of 10^{-3} gives grade 3 ('Fair'). These relate to C/N ratios, measured in a bandwidth of one-half the bit rate (i.e. 364 kHz), of 11.4 dB and 9.8 dB respectively, according to theory. A dramatic improvement in quality thus results from a modest improvement in C/N. We shall take 12 dB as our C/N objective. In the absence of interference, this would offer grade 4.5 quality, and would still give grade 3 when the effective C/N is degraded by 2 dB by the presence of interference (which may be treated as additive noise – see Section 5).

We can now construct link budgets as shown in Table 1, where the figures for analogue FM accord with Ref. 10 (except for the noise temperature already discussed) and refer to mono reception. The link margin L has been left as a parameter. As already mentioned, a range of 6 to 33 dB is discussed in Ref. 10. The figure of 6 dB is appropriate for high angles of elevation (i.e. low-latitude areas served from the geostationary orbit, or high-latitude served from a Molniya orbit), in rural areas. At the other extreme 33 dB is needed for high-reliability service with low angles of elevation. There is some evidence that these margins will increase with frequency.

It will be noted that the digital solution requires an EIRP which is 3.6 dB greater than for FM. However, this is for *two* channels rather than one. In effect, a penalty of only 0.6 dB is paid for the greater flexibility of the digital system. Furthermore, the quality of the digital system improves more rapidly as the C/N increases than is the case for FM.

To translate the EIRP into transmitter output power we subtract the antenna gain in dBi. This depends on the beam size, e.g. 43.2 dBi for the UK beam of WARC-77. This gives a transmitter power of $(5.4 + L)$ dBW for FM and $(9 + L)$ dBW for digital stereo. Thus the most pessimistic margin, applicable to built-up areas at high latitudes served from the geostationary orbit would require 7 kW for

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* Ref. 12 gives an interesting account of one of the experiments from which the range of margins was derived.

† This increase in C/N to achieve subjectively-equivalent noise performance in stereo is typically 16 dB with the Zenith–G.E. system.

	Modulation type Signal capacity	FM mono	Digital, VSB 2-PSK stereo
	Carrier deviation *or* Bit rate	±75 kHz —	— 728 kbit/s
	Noise bandwidth	250 kHz ≡ 54 dB Hz	364 kHz ≡ 55.6 dB Hz
plus	carrier-to-noise ratio	10 dB	12 dB
plus	coupling loss	1 dB	
less	receiving antenna gain	3 dB	
less	effective area of isotropic antenna at 1 GHz	-21.4 dB m^2	
plus	receiving system noise temperature*	600 K ≡ 27.8 dB K	
plus	Boltzmann's constant	-228.6 dB W Hz^{-1} K^{-1}	
plus	link margin	L dB	
equals	line-of-sight PFD at edge of beam (-3 dB)	$(-117.4 + L)$ dB W m^{-2}	$(-113.8 + L)$ dB W m^{-2}
	Maximum spreading loss	163 dB	
∴	Beam-centre EIRP	$(48.6 + L)$ dB W	$(52.2 + L)$ dB W
	On-axis transmitting-antenna gain	G dBi	
	Transmitter power into antenna	$(48.6 + L - G)$ dB W	$(52.2 + L - G)$ dB W

* Value of 600 K conforms with Ref. 11. Ref. 10 used 2000 K, and therefore required 5.2 dB more power.

Table 1: Link budget example

FM or 16 kW for digits; at the other extreme, a low-latitude rural area of similar size to the UK could be served with 14 W (FM) or 32 W (digits).

Clearly, the link margin necessary is of crucial importance in determining the feasibility of satellite sound broadcasting. More study is required, especially for the digital case where the effect of multipath on sound quality is different from that experienced using FM, so that it may not be appropriate to make the same allowance for the two cases. The possibility of using a Molniya orbit to serve high-latitude countries with a high angle of elevation is also of interest. In this case the link margin in urban areas might be expected to be smaller than when using the geostationary orbit, while in addition it should be possible to increase the gain of vehicle-mounted antennas. This might not be the case for portables, but then there is often the freedom to change location slightly to avoid the worst effects of multipath.

5. Use of spectrum

We have noted that no frequency allocation exists at present for sound satellite broadcasting and the desirable range is extensively used by terrestrial services. If a band is to be secured it is important not to make excessive demands for spectrum. The same frequency must therefore be re-used many times to serve separate areas. The extent to which this may be done depends on the degree of (planned) mutual interference which may be tolerated. This is commonly expressed in the form of a protection ratio – the ratio of carrier to interference (C/I) which must be exceeded to ensure satisfactory quality. This depends on the difference in frequency between the wanted and interfering signals and also on the characteristics of both signals (e.g. modulation system, bandwidth).

Ref. 10 quotes the results of a planning exercise for Africa and Europe, using FM and parameters similar to those used in the TV DBS Plan, which show that to provide each country with one national programme would require about 60 channels. These would be separated by 150 kHz and thus occupy about 9 MHz in all. The exercise assumed monophonic reception. Stereo reception would only be possible at fixed locations where a more elaborate antenna would provide the necessary improvement in both C/N and discrimination against interferers (at different orbit locations) so that the more stringent protection ratio for stereo could be satisfied.

The protection ratio required for FM is quite high. For continuous interference, with mono reception, Ref. 14 gives 36 dB (co-channel) and 8 dB (adjacent-channel at 150 kHz spacing). For stereo, the protection ratios are significantly higher: 45 dB

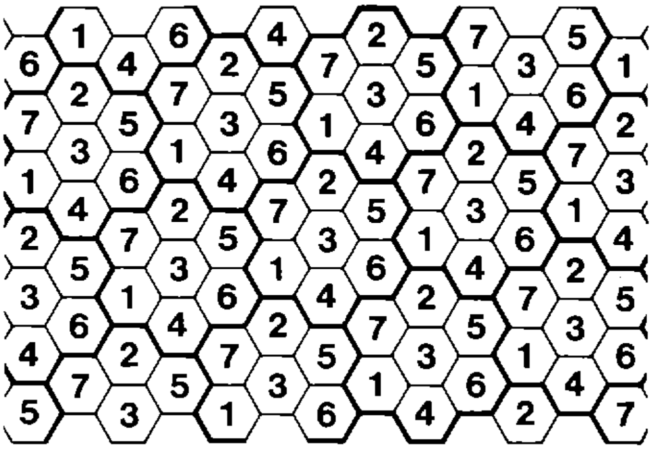

Fig. 4 – Lattice of hexagonal service areas having a seven-cell repeat structure. The number in each hexagon denotes the lowest-numbered channel allocated to that area; it is also allocated every seventh channel above that. For example, the centre cell is served by channels 3, 10, 17, 24 . . .

for co-channel interference (CCI) and 18 dB for adjacent-channel interference (ACI). This explains the limited frequency re-use implicit in the requirements for 60 channels for one programme per country.

For digital modulation, the protection-ratio requirements tend to be lower, and this should offset the intrinsic greater bandwidth. Full design parameters for the digital system under discussion are not yet settled so it would be inappropriate to embark on a full-scale planning exercise. However, an indication may be gained by the following simplified approach. Fig. 4 shows an idealised lattice of service areas. It is assumed that each area is to be served with N programmes, using $7N$ channels in all in this example. The regularity of the arrangement is such that whatever service area is considered, the locations of the areas served by potentially-interfering signals follow another regular pattern, Fig. 5, so the calculation of interference need only be done once, all areas being equally served. If we assume that linear distance is proportional to off-axis angle at the satellite transmitter, and we have the radiation pattern of the transmitting antenna, the level of interference is readily estimated. For example, if the beam size is chosen so that the wanted signal is 3 dB down at the vertices of the hexagonal service area, and we use the WARC-77 antenna pattern we obtain the following, using noise power addition of the interferers, which are assumed to be uncorrelated:

$$\text{carrier-to-total CCI ratio} \approx 16.1\,\text{dB}$$

$$\text{carrier-to-total ACI ratio} \approx -1.1\,\text{dB}$$

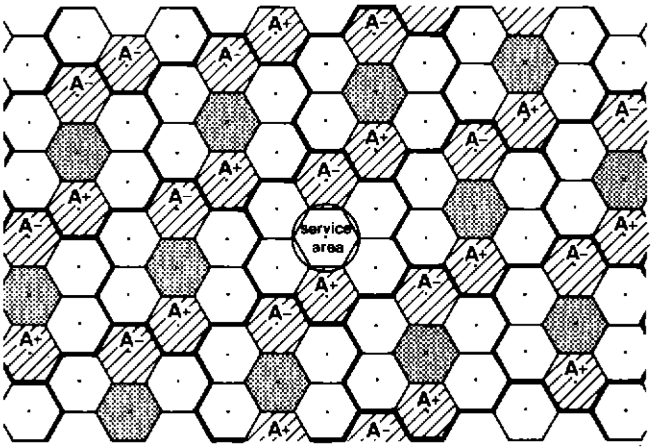

Fig. 5 – Location of areas served by potentially-interfering transmissions.

Whichever service area in the regular structure of Fig. 4 is examined, the same regular pattern of potential-interferer locations results. The dot-shaded areas are served by the same channel as the wanted service area, while those hatched are served by upper (A+) and lower (A–) adjacent channels respectively.

These are for the worst location at the edge of the service area; at the centre CCI improves by 3 dB and ACI by about 6 dB.

The significance of these C/I ratios can be assessed if we assume that the effect of interference between digitally-modulated signals is equivalent to the addition of the same power of noise. The significance of ACI is reduced by a factor dependent on the channel spacing – a figure of say 20 dB is appropriate. The overall effective C/N now results from the combination of thermal noise, CCI and ACI, whose C/N values individually are, in the limit, 12, 16.1 and 18.9 dB respectively, giving the value of 10 dB. The thermal C/N of 12 dB has in effect been degraded by 2 dB by the interference, as assumed in deriving the link budget.

This suggests that coverage might be achieved using only 7 channels for one programme to each service area. Filtering requirements should be easily satisfied at say 1 MHz channel spacing, giving a requirement of 7 MHz per stereo national programme. However, real countries do not fit a regular hexagonal lattice! Only a full planning exercise can give results genuinely comparable with those for FM, quoted from Ref. 10. Nevertheless, it appears possible that a digital system which offers stereo or multi-channel reception with portable or mobile receivers, as well as fixed ones, need not be any more greedy of spectrum than the FM system which only offers stereo to fixed receivers.

6. Economic factors

The economics of introducing a new broadcast service depend on many factors, especially the context in which it is to be introduced. A developed country, with broadcasting already well established, might introduce a new service to provide better quality of reception or greater variety of programmes, or simply another marketable product. A developing country might be faced with the problem of providing nationwide broadcasting for the first time. Without trying to judge actual costs, whose magnitude and significance will vary from country to country and with time, some of the visible and hidden costs of broadcasting are listed below:

A network of terrestrial transmitters needs:

- many transmitting sites, with transmitters, aerials, and accommodation;
- roads to provide access to them;
- power distribution or local generation to provide power to the transmitters;
- staff to operate and maintain them.
  (The cost of electricity is significant.)

Satellite broadcasting needs:

- a satellite,* and provisions for back-up in event of failure;
- one earth station, comprising the feeder-link transmitter and facility for TT & C,† possibly situated at the studio centre, obviating the need for extra roads, power distribution and communications links;
- less staff.
  (The feeder-link transmitter requires very little power compared with a network of broadcast transmitters.)

Although satellites are very expensive, clearly so is the provision of a major terrestrial network absolutely from scratch, as in a developing country. A satellite gives instant coverage of the whole area from the start of service but all the costs are incurred then too.

In either case, the listening public must have suitable receivers.

7. Further work

The link margin is a dominant factor in the link budget – the range of power requirements from 14 W to 16 kW listed in our examples encompasses the range of satellite technology from 'off-the-shelf' to 'requiring significant development'. Further work should determine more precisely what is needed, at various frequencies, with various modulation systems – if these affect the result – and consider the use of Molniya orbits as well as the geostationary orbit.

Further study of digital systems is also desirable:

> Is the proposal presented here the best choice?
> What allowance is actually needed for interference, including the effect of varying channel spacing?
> To what extent might sharing be possible?

When the parameters have been refined, a planning exercise may be carried out to determine what total bandwidth is needed to serve real countries with non-geometric boundaries. With this knowledge, it will be possible to make the case for a specific frequency band allocation at the second session of the WARC GSO Conference.

8. Conclusion

Broadcasting of sound programmes from terrestrial transmitters at present provides a variety of services – on a scale from local to international – to receivers used in a variety of situations: portable, mobile or fixed. The frequency bands used for broadcasting are congested and limit the scope for expansion of services.

Broadcasting sound programmes from a satellite to a national or regional (sub-national) area, to be received by portable or mobile receivers as well as fixed ones, is technically possible. At present no suitable frequency allocation is available; the study of systems which minimise the demands to be made for spectrum is therefore appropriate. Sample calculations have been presented which suggest that a digital modulation system may compare well with conventional FM in respect of power requirements and spectrum efficiency, while offering greater flexibility and extending stereo (or multi-channel) reception to portable or mobile receivers.

Satellite broadcasting is more attractive where a high elevation angle is possible. This makes it particularly suitable for developing countries at low latitudes, which may be served from the geostationary orbit. The ease with which nationwide coverage may be obtained without heavy demands for infrastructure is also of benefit to such countries. The benefits of high elevation angle are available to the high-latitude countries by the use of different orbits, such as the Molniya type; in this case there is a cost penalty because of the need for three operational satellites instead of one.

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* One, in geostationary orbit, or several in other orbits if 24-hour service is required.

† Telemetry, tracking and command – the functions needed to establish and maintain correct operation of the satellite.

The link margin required to allow for the effects of shadowing or multipath is a critical factor. Further study is needed to determine the variation of appropriate margin with elevation angle, especially when using digital modulation. The detailed parameters of digital modulation systems and their impact on spectrum usage, including the difficulty of sharing with other services, also require further study: digital modulation appears to offer useful advantages over FM systems considered previously. With this knowledge, the spectrum requirements for planning of such services may be estimated so that a specific frequently allocation can be sought at the second session of the WARC GSO Conference in 1988.

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